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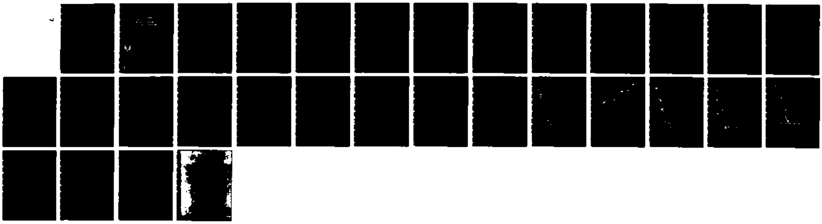

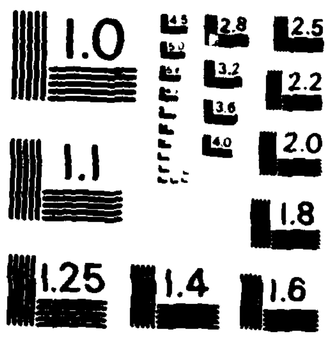

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TECHNICAL REPORT ARLCB-TR-84009

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J-R CURVE DETERMINATION USING PRECRACKED CHARPY SPECIMENS AND THE LOAD-DROP METHOD FOR CRACK GROWTH MEASUREMENTS

JOSEPH A. KAPP

APRIL 1984

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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J-R curves for two aluminum alloys, a titanium alloy and a high strength-low alloy steel at two different strength levels were determined using precracked Charpy specimens. Three methods were used to measure crack growth: (1) multi-specimen, (2) compliance unloading, and (3) the "load-drop" method. The "load-drop" method assumes that crack growth occurs only after peak load has been attained and the amount which the load decreases after peak load is related to

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20. ABSTRACT (CONT'D)

the size of the uncracked ligament. Comparisons between the three methods for all of the materials show remarkably similar J-R curves. Also, using these curves to determine a J_{Ic} indicates very little difference between the "load-drop" method and the others in the measurement of toughness.

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INTRODUCTION

A measure of fracture toughness, whether it be K_{Ic}, J_{Ic}, J-R, or K-R is useful in the characterization of materials, but the use of these property measurements as a quality-control device is not yet routine except in a few fracture critical instances. The primary reason for this is the cost of such toughness tests, in addition to the always present question of validity, mainly the size validity criterion. In many engineering applications, it is not possible to obtain a valid test within the limits of the size of the material stock we must work with. To alleviate these problems, a test should be developed which has a significantly relaxed size requirement and a minimum amount of analysis necessary to obtain the measurement. Attempts have been made to accomplish this; most noteworthy are the strength ratio method of Succop and Brown (ref 1) using precracked Charpy samples and the equivalent energy method of Witt (ref 2) using ASTM Standard E-399 type specimens. It is the purpose of this report to expand on these methods using J-integral analysis and precracked Charpy samples.

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[1] Succop, G. and Brown, W. F., Jr., "Estimation of K_{Ic} From Slow Bend Precracked Charpy Specimen Strength Ratios," ASTM STP 632, (W. F. Brown, Jr. and J. G. Kaufman, Eds.), American Society for Testing and Materials, 1977, pp. 179-192.

[2] Witt, F. J. and Mager, T. R., "A Procedure for Determining Bounding Values on Fracture Toughness K_{Ic} at Any Temperature," ORNL-TM-3894, Oak Ridge National Laboratory, Oak Ridge, TN, 1972.

Recently, many investigators have used precracked Charpy samples to perform J_{Ic} tests (refs 3-5). These studies have shown that the precracked Charpy test configuration can adequately be applied to an accurate measurement of J_{Ic}. But the testing universally has been shown to be cumbersome, requiring several specimens or substantial instrumentation to accomplish the task of determining the J-R curves from which J_{Ic} is measured. The method outlined below allows for the determination of an entire J-R curve using a single specimen and a minimum of instrumentation. Comparisons between the R curves developed using the more standard methods of measuring crack growth and the "load-drop" method show very little difference. Furthermore, the J_{Ic} measurements are also very close using any of the techniques.

THE "LOAD-DROP" METHOD

As stated above, a significant obstacle in the application of precracked Charpy samples to J testing is the crack growth measurement technique. Three crack growth measurement techniques were employed in this work, the multi-specimen and the compliance unloading methods are well-known. The "load-drop" method is also a single specimen method, with which we assume that crack extension is related to the amount of load shed after the peak load has been attained. If we test materials that are sufficiently ductile with a cracked sample that has a small uncracked ligament, substantial plastic flow should

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[3]Neal, B. K., Int. J. Pres. Ves. Piping, Vol. 12, 1983, pp. 207-227.
[4]Kapp, J. A. and Underwood, J. H., "Single Specimen J-Based Fracture Toughness Test for High-Strength Steels," ASTM STP 791, (J. C. Lewis and G. Sines, Eds.), American Society for Testing and Materials, 1983, pp. II402-II414.
[5]Underwood, J. H., in Fracture Mechanics (11th Conference), ASTM STP 677, American Society for Testing and Materials, 1979, pp. 463-473.

develop on the uncracked ligament prior to crack extension. If the amount of plastic deformation is sufficient, such that the limit load is approached, the moment (M) which can be supported by the cracked specimen is given as (ref 6):

$$M = 0.36\ Bb^2\ \sigma_f \tag{1}$$

where B and b are the through thickness and the remaining ligament respectively, and σ_f is the flow strength. In three-point bending, M = PS/4 where P is the load and S is the distance between supports. Eq. (1) can be restated as:

$$P = \frac{1.44\ Bb^2\ \sigma_f}{S} \tag{2}$$

If we let $b = b_o$, the initial remaining ligament, then the maximum load achieved in the test, P_{max}, would be

$$P_{max} = \frac{1.44\ Bb_o^2\ \sigma_f}{S} \tag{3}$$

When crack extension occurs, the remaining ligament is decreased by the amount of crack growth Δa or:

$$b_{\Delta a} = b_o - \Delta a \tag{4}$$

Furthermore, since the remaining ligament is reduced, the load that the reduced ligament can support, $P_{\Delta a}$, should also be reduced to a value which is proportional to $b_{\Delta a}^2$, or

$$P_{\Delta a} = \frac{1.44\ Bb_{\Delta a}^2\ \sigma_f}{S} \tag{5}$$

---

[6] Rice, J. R., Paris, P. C., and Merkle, J. G., in Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, American Society for Testing and Materials, 1973, pp. 231-245.

The relative "load-drop" associated with an increment of crack growth reducing the ligament from b_o to $b_{\Delta a}$ is obtained by manipulating Eqs. (3) and (5).

$$\frac{P_{\Delta a}}{P_{max}} = \frac{b_{\Delta a}^2}{b_o^2} \tag{6}$$

The quantities $P_{\Delta a}$ and P_{max} are easily determined from the load-displacement trace obtained during the test, and b_o is easily measured on the broken specimen. Thus with Eqs. (4) and (6), we have a method for estimating the amount of crack growth on a single specimen requiring no special instrumentation.

The above analysis is not intended to be either absolutely correct or rigorous. The two assumptions from which Eq. (6) evolves are probably not met in most cases. Some crack extension may be occurring before the maximum load is attained. Also, Eq. (5) is derived assuming that the ratio of P/b^2 is a constant beyond maximum load. Lin and Rosenfield (ref 7) and Lai and Zhang (ref 8) have shown that P/b^2 is a function of displacement beyond maximum load. Although these assumptions are technically wrong, they do hold approximately and sufficiently for the intended purpose of this work as will be demonstrated below.

MATERIALS

Data were collected using five materials, two steels, two aluminum alloys, and a titanium alloy. The steels were both ASTM A723 Grade 1 pressure

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[7]Lin, L.-H. and Rosenfield, Int. Journ. of Fracture, Vol. 20, 1982, pp. 103-115.

[8]Lai, Z. and Zhang, J., Journal of Testing and Evaluation, Vol. No. 5, September 1983, pp. 340-345.

vessel steels heat treated to two different strength levels, Class 1 and Class 4. The aluminum alloys were 6061-T651 and 7075-T7351 with the specimens oriented in the L-T direction according to ASTM Standard E-399, and the titanium alloy was 6Al-4V-Titanium in the annealed condition. The titanium alloy was obtained in round bars; the specimens tested were in the L-R orientation. The mechanical properties for all the materials are given in Table I.

TABLE I. ROOM TEMPERATURE MECHANICAL PROPERTIES OF THE MATERIALS TESTED

Material	0.1% Yield Strength MPa	Ultimate Strength MPa	Fracture Toughness	
			MPa$\sqrt{m}$	(kJ/m^2)*
A723 Grade 1, Class 1	820	990	147	(109)[a]
A723 Grade 1, Class 4	1230	1320	128	(80)[b]
6061-T651	282	312	53	(40)[c]
7075-T7351	517	590	35	(18)[c]
6Al-4V-Ti	946	1000	44-66	(19-42)[c]

a). Estimated by J analysis of invalid K_{Ic} tests.
b). Valid K_{Ic} measurements.
c). Estimated from Handbook values.
*Toughness given in units of J are simple conversions from K data assuming plane stress conditions.

RESULTS AND DISCUSSION

The results from testing the A723, Grade 1, Class 1 steel are presented in Figures 1 and 2. Figure 1 shows the J-R curves generated with the "load-drop" analysis compared with the values of crack extension measured on the fracture surfaces. For the steel samples, the heat tinting method was used to observe the amount of crack extension. It is clear that the material tested exhibited a great deal of scatter from specimen to specimen. As little as 140 kJ/m^2 energy release rate resulted in more than 1.2 mm of crack extension in the weakest sample, while the strongest sample required the application of an energy release rate of almost 385 kJ/m^2 to produce only about 1.0 mm of crack extension. The variation in properties is attributed to a nonuniform thermomechanical treatment of the forging from which the specimens were taken. The low fracture properties were associated with a dendritic microstructure and the high fracture property samples had a fine martensitic microstructure. Since we tested nonidentical samples, the multi-specimen method of producing a J-R curve was not applicable in this case.

Two observations can be made from Figure 1. Of the six specimens tested, two tests were terminated when the load was at a maximum. One test was just as P_{max} was attained, the other just as the load started to drop off. The measured amount of crack extension falls on the blunting line. This suggests that the basic assumption of no significant crack growth until after P_{max} is valid for this material. The second observation is that for larger crack extensions, the value of Δa predicted with the "load-drop" method is in reasonable agreement with the measured value from the fracture surfaces.

Crack extension was also determined for three specimens by the compliance unloading method as outlined in ASTM Standard E813. The resulting J-R curves from these tests are shown in Figure 2. These results clearly show that the J-R curves determined with the "load-drop" method are excellent approximations to the actual material properties. J_c determined from either the compliance unloading measurements or the "load-drop" measurements, shows that good agreement is obtained.

The J-R curve developed for the A723, Grade 1, Class 4 steel using the multi-specimen method is shown in Figure 3. The open symbols are the "load-drop" estimate of total crack extension and the curves are the total "load-drop J-R curve for each sample. The closed symbols are from actual measurements on the fracture surfaces. In all cases, the "load-drop" measurement of Δa was somewhat less than the fracture surface measurement. This resulted in estimates of J_c from "load-drop" being somewhat higher than the value determined with the fracture surface measurements. This may be the result of dealing with a somewhat more brittle material than in the previous case. There may have been a small amount of crack extension before peak load.

The comparison of the compliance unloading and "load-drop" J-R curves for the A723 Grade 1, Class 4 steel is shown in Figure 4. Two specimens were tested in this manner and the agreement is quite good. For the specimen represented with the triangles, there is very little difference between the data developed using either method, although the "load-drop" method overestimates crack growth a little at high J values, as compared with the unloading measurements. The instance is reversed for the data plotted as circles where large crack extensions are approximated very well while small

crack extensions are overestimated with the "load-drop" method.

Comparing the "load-drop" method with the compliance unloading method for 6061-T651 gives us Figure 5. Good agreement again is obtained and the J-R curves generated by either method are probably a good estimate of the material property. Some scatter is also encountered with these test results, but the value of J_c from either analysis technique is comparable with what would be expected based on the expected toughness of this material from Table I.

Only the multi-specimen method was used in testing the 7075-T7351 and the annealed 6Al-4V-Ti alloy. The results of the tests performed on these materials appear in Figure 6 for aluminum and in Figure 7 for titanium. The aluminum results show that "load-drop" sometimes overestimates actual crack extension, and in other cases underestimates it. There is a variation in J_c using the "load-drop" analysis from specimen to specimen, ranging from about 18.6 kJ/m^2 to 21.0 kJ/m^2. Applying the multi-specimen method with fracture surface measurements, J_{Ic} is about 22.7 kJ/m^2, and using the final estimated crack extensions from "load-drop", J_c is 23.8 kJ/m^2. All of these toughness values are in general agreement with the values of toughness for 7075-T7351, cited in Table I.

Finally, the results of the multi-specimen testing of the annealed 6Al-4V-Ti are given in Figure 7. All specimens using "load-drop" analysis give a good estimate of J_c determined with the multi-specimen technique, although one specimen seemed to be a little tougher than the others. J_c from the individual specimens ranges from 30.6 kJ/m^2 to 39.4 kJ/m^2 with most of the data at the lower end of the range. Using the fracture surface measurements in the multi-specimen technique, J_c is 30.3 kJ/m^2 compared with 32.0 kJ/m^2

using the estimated crack extensions from each sample by "load-drop" analysis. Comparing these toughness values with the expected toughness from Table I suggests that the "load-drop" analysis method results is an adequate measure of toughness.

Summarizing the results of estimating a value of toughness using the J-R curves generated gives us Table II. In all cases using compliance unloading or multi-specimen methods, the values of J_c quoted were determined by the intersection of a least squares line of all of the crack growth with the blunting line. J_c values from "load-drop" calculations were from extrapolating the crack growth curves to the blunting line. For the two steels tested, comparing J_{Ic} values determined by using established techniques and the "load-drop" method suggest that using the "load-drop" method gives a reasonable estimate of J required to cause crack growth. There was so much scatter from the A723, Grade 1, Class 1 steel, that the multi-specimen method could not be applied. But, comparing the "load-drop" and compliance unloading results, reasonable agreement was obtained, although the J_c results may be misleading when compared with the expected value from Table I. This was probably the result of the ability to measure properties on a much more local basis with the small precracked Charpy samples. Any gradient in mechanical properties is easily determined with small specimens.

TABLE II. SUMMARY OF J_c RESULTS (ALL VALUES IN kJ/m^2)

Material	Expected (Table I)	Multi-Specimen	Compliance Unloading	Load Drop
A732, Grade 1, Class 1	104	-	95-155	75-250
A723, Grade 1, Class 4	80	102	110-125	100-115
6061-T651	40	-	42-47	39-42
7075-T7351	18	21	-	18-22
6Al-4V	19-42	32	-	29-40

The results from the testing of the other materials suggest that these materials were somewhat more homogeneous since much less scatter was evident. In all these cases the values of J_c determined using the "load-drop" method were in excellent agreement with the results obtained with the established techniques. Furthermore, the measured values of J_c for the two aluminum alloys and the titanium alloy are in good agreement with the expected values from Table I. The only exception to this was the A723, Grade 1, Class 4 steel where all the J_c values were substantially higher than the expected value based on K_{Ic}.

Since the basis of the "load-drop" method is the absence of crack growth prior to P_{max}, and the amount of crack extension is based on the elastic-plastic limit load, a comparison of the theoretical limit load and P_{max} is warranted. This comparison is made in Table III, where the ratio of measured P_{max} to the limit load by Eq. (2) is given. These ratios show that for 7075-T7351 and 6Al-4V-Titanium, P_{max} was as little as 67 percent of the limit load,

but using a J analysis still results in a good measure of toughness. For the other three materials tested, the actual value of P_{max} was very nearly the limit load.

Another manner in which to analyze the slow bend precracked Charpy specimens is that outlined by Succop and Brown (ref 1). When P_{max} is substantially below the limit load, the empirical formula has been shown to apply (ref 1):

$$K_{Ic} = \frac{\sigma_c \sqrt{W}}{2.10} \tag{7}$$

where

$$\sigma_c = \frac{1.5\ P_{max}\ (S/W)}{BW(b_o/W)^2} \tag{8}$$

Using Eqs. (7) and (8), the data developed in this study may be used to estimate toughness. Realizing that K and J are equivalent, the value of toughness given by Eq. (7) can be represented in terms of J. This treatment of the data results in the third column in Table III. As would be expected, this analysis gives a good estimate when P_{max} is substantially less than the theoretical limit load. The toughness values of both materials that responded this way (7075-T7351 and 6Al-4V-Ti) are in good agreement with toughness values measured using conventional J_c techniques or "load-drop" J_c analysis. For those materials that responded such that the limit load was very nearly attained, the use of Eq. (7) is a substantial underestimate of toughness.

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[1]Succop, G. and Brown, W. F., Jr., "Estimation of K_{Ic} From Slow Bend Precracked Charpy Specimen Strength Ratios," ASTM STP 632, (W. F. Brown, Jr. and J. G. Kaufman, Eds.), American Society for Testing and Materials, 1977, pp. 179-192.

TABLE III. COMPARISON OF TOUGHNESS BY VARIOUS METHODS

Material	$\frac{P_{max}}{P_{max}\ (Eq.\ 2)}$	J_c (Table I)	J_c (ref 1)	J_c (Conventional)	J_c (Load Drop)
A723, Grade 1, Class 1	0.82-0.95	104	48-56	95-155	75-250
A723, Grade 1, Class 4	0.86-0.96	80	61-76	102-125	100-115
6061-T651	1.04-1.11	40	15-18	42-47	39-42
7075-T7351	0.67-0.77	18	21-28	21	18-22
6Al-4V-Ti	0.67-0.74	19-42	43-53	32	29-40

[1]Succop, G. and Brown, W. F., Jr., "Estimation of K_{Ic} From Slow Bend Precracked Charpy Specimen Strength Ratios," ASTM STP 632, (W. F. Brown, Jr. and J. G. Kaufman, Eds.), American Society for Testing and Materials, 1977, pp. 179-192.

Thus, using a J analysis incorporating the "load-drop" estimate of crack extension on precracked Charpy samples, a good estimate of toughness is obtained in a variety of materials with a wide range of properties.

CONCLUSIONS

Using the simple "load-drop" technique of estimating crack extensions for precracked Charpy specimens of relatively ductile materials yields a good approximation of the J-R curves for these materials. This method may be a useful technique to measure toughness on a quality control basis, or may be helpful in analyzing invalid K_{Ic} or strength ratio tests on small samples.

REFERENCES

1. Succop, G. and Brown, W. F., Jr., "Estimation of K_{Ic} From Slow Bend Precracked Charpy Specimen Strength Ratios," ASTM STP 632, (W. F. Brown, Jr. and J. G. Kaufman, Eds.), American Society for Testing and Materials, 1977, pp. 179-192.
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8. Lai, Z. and Zhang, J., Journal of Testing and Evaluation, JTEVA, Vol. No. 5, September 1983, pp. 340-345.

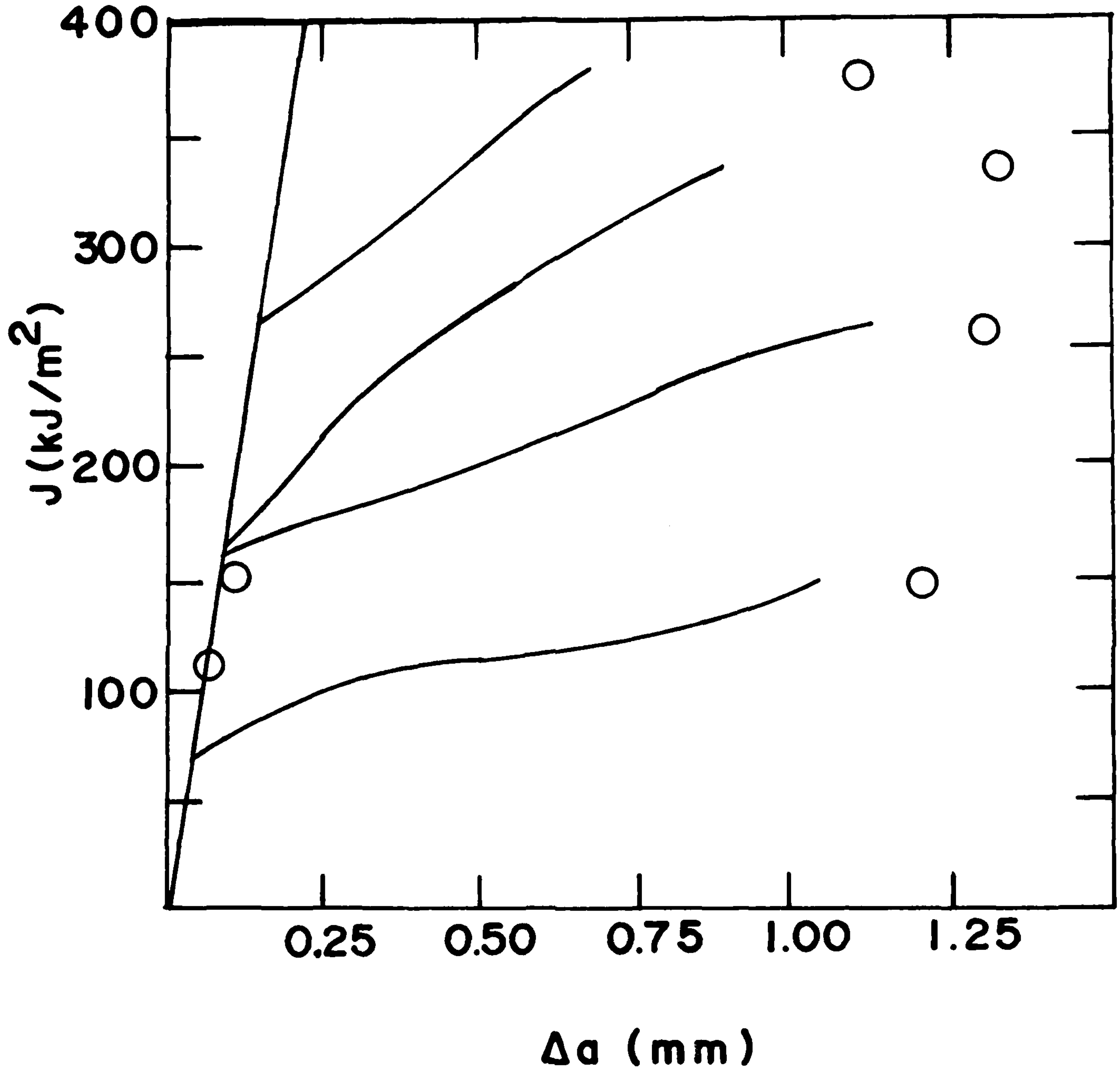

Figure 1. J-R curve for A723, Grade 1, Class 1 steel using the multi-specimen method. The symbols are fracture surface crack growth measurements. The lines are the J-R curves for each sample using the "load-drop" method.

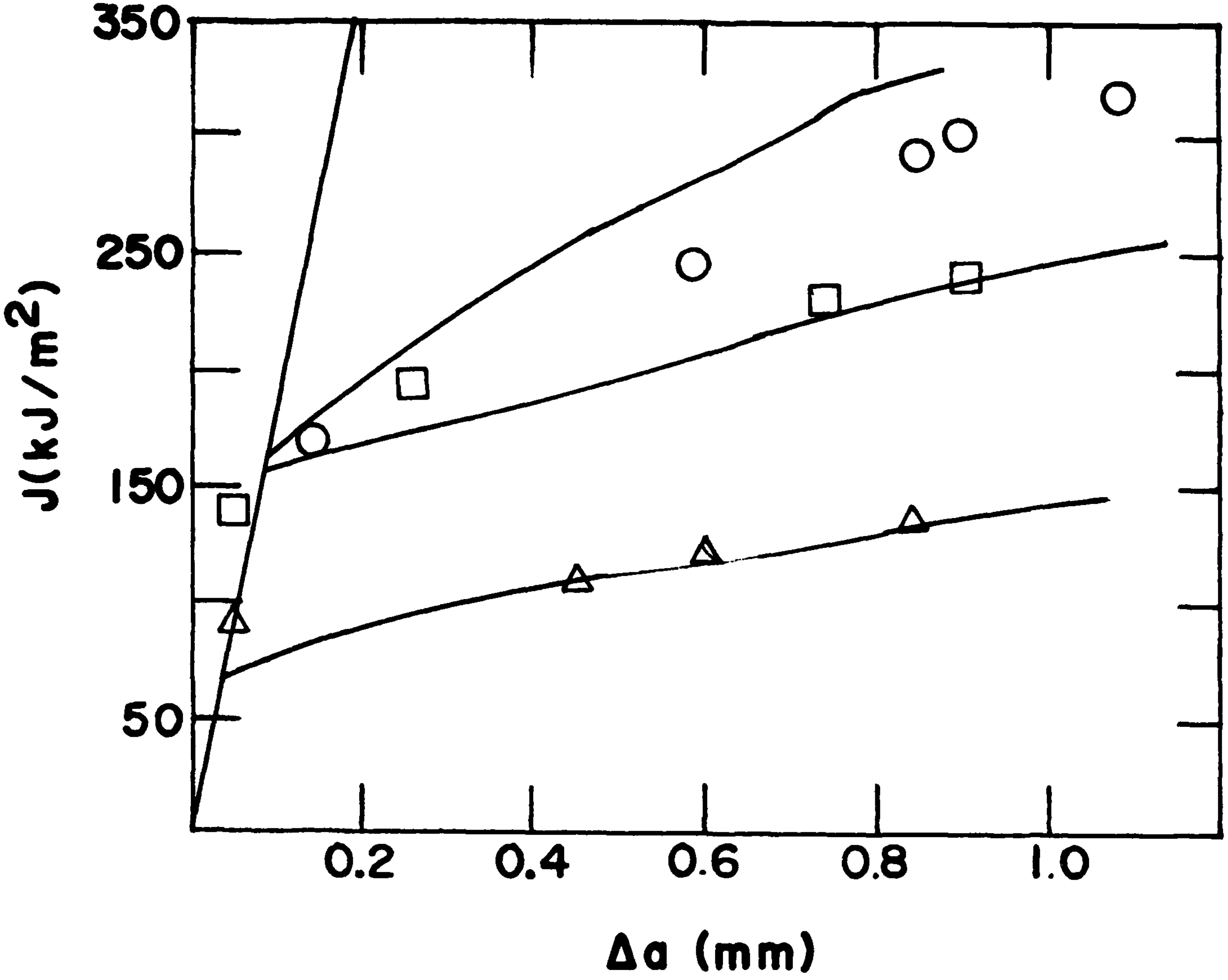

Figure 2. J-R curve for three specimens of A723, Grade 1, Class 1 steel using the compliance unloading method. The symbols are the calculated crack growth from unloading and the lines are the J-R curves for the three specimens using the "load-drop" method.

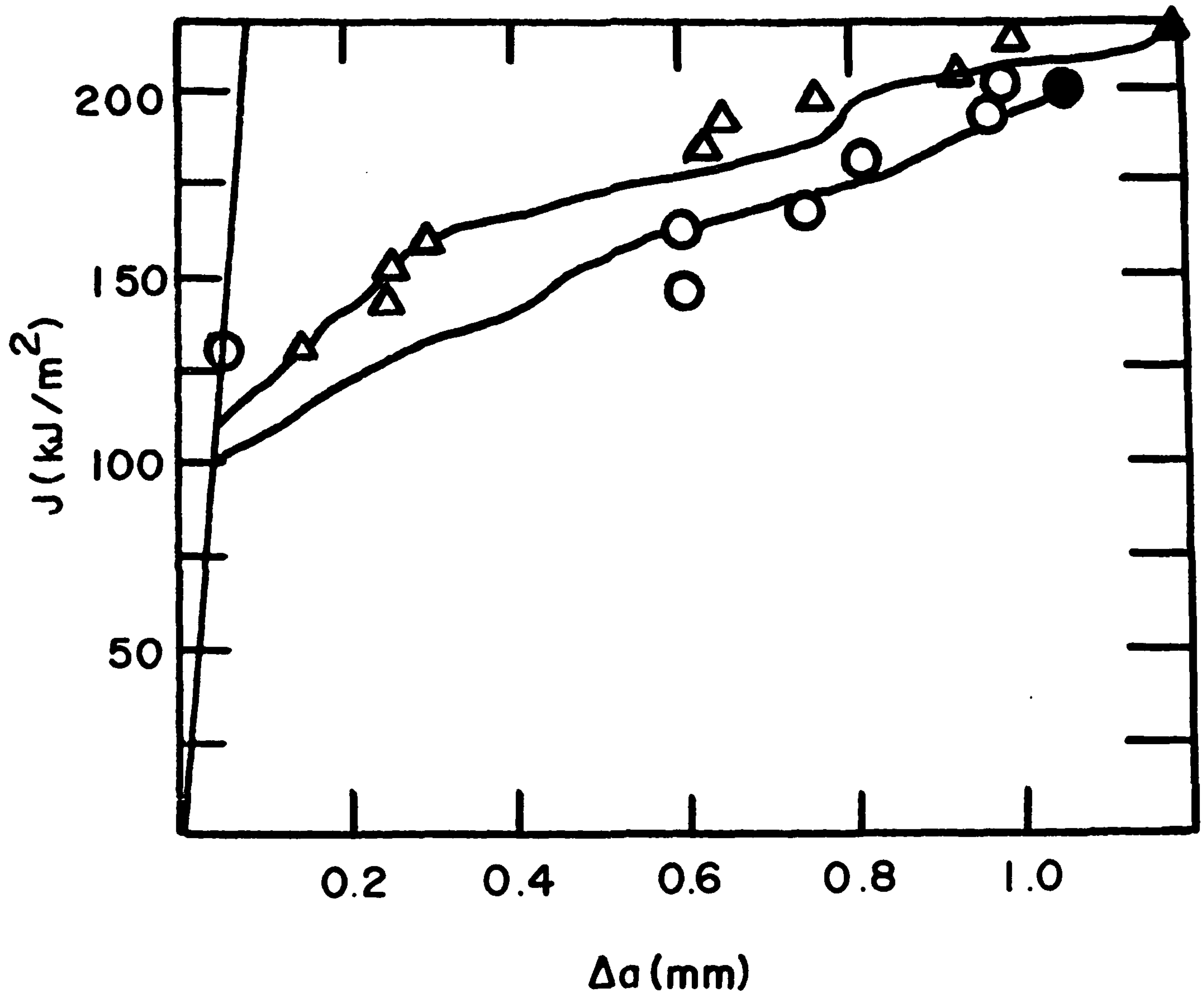

Figure 3. The multi-specimen J-R curve for A723, Grade 1, Class 4 steel. The solid symbols are the fracture surface crack growth measurements. The open symbols represent the final amount of crack extension estimated by the "load-drop" analysis and the curved lines are the entire J-R curve by "load-drop" estimates.

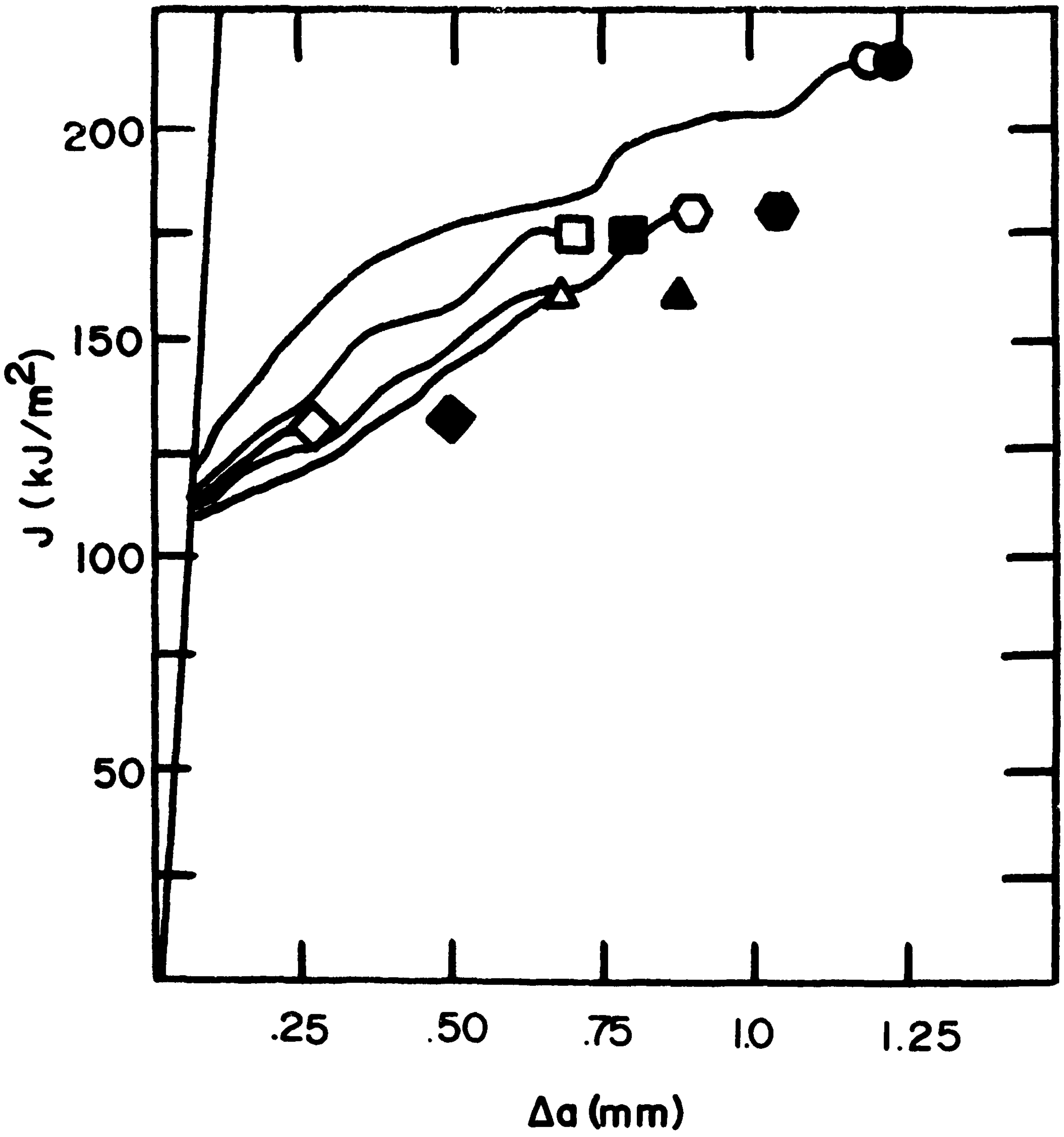

Figure 4. J-R curves for two specimens of A723, Grade 1, Class 4 steel using the compliance unloading method. The open symbols are the J-Δa points determined from compliance, the solid symbols are the final amounts of crack growth estimated from "load-drop," and the lines are the entire J-R curves using "load-drop" analysis.

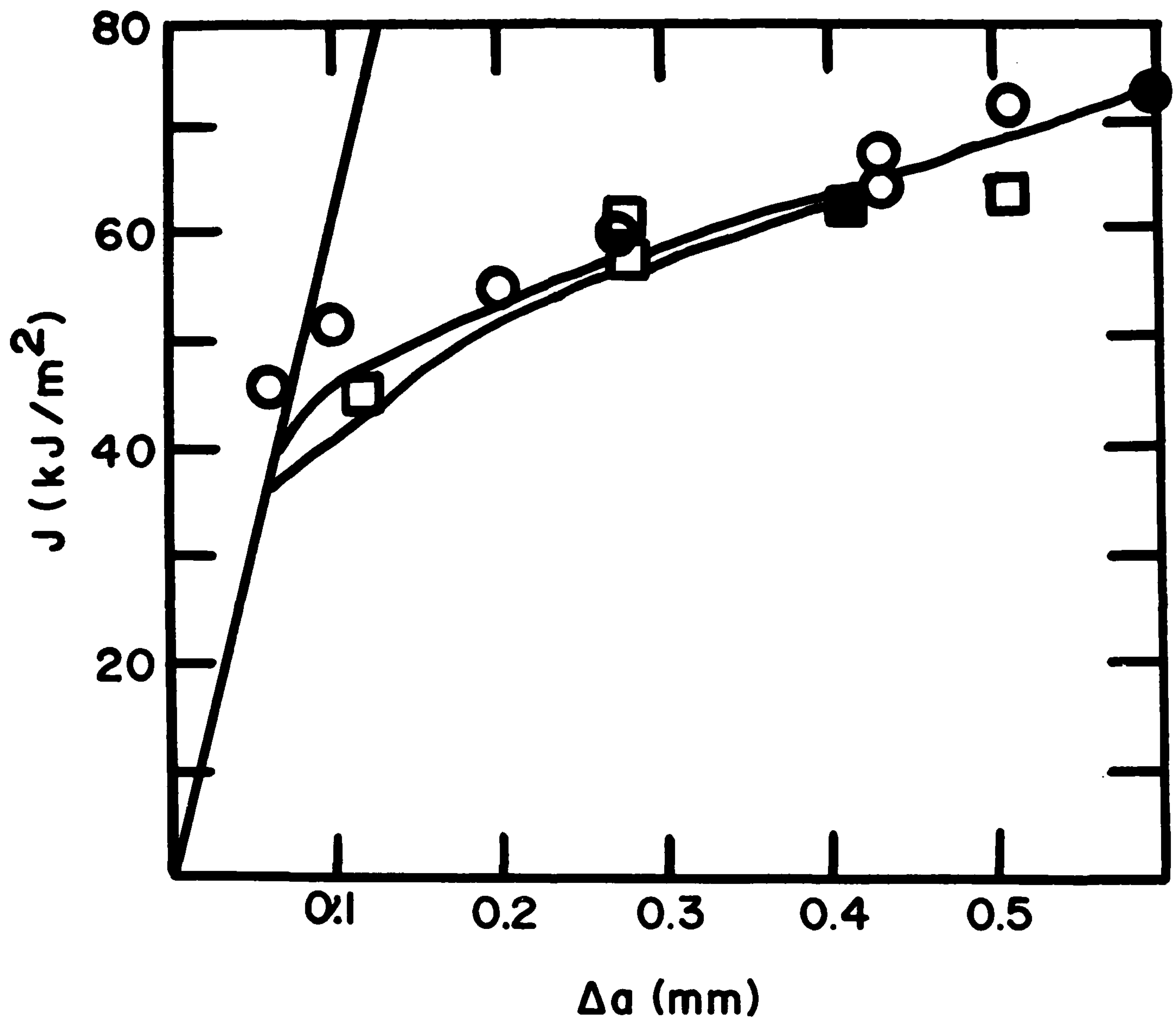

Figure 5. Compliance unloading results for two specimens of 6061-T651 aluminum. The open symbols are the J-Δa points from compliance and the solid symbols are the estimates of the total amount of crack extension from "load-drop." The curves are the estimates of the J-R property using "load-drop."

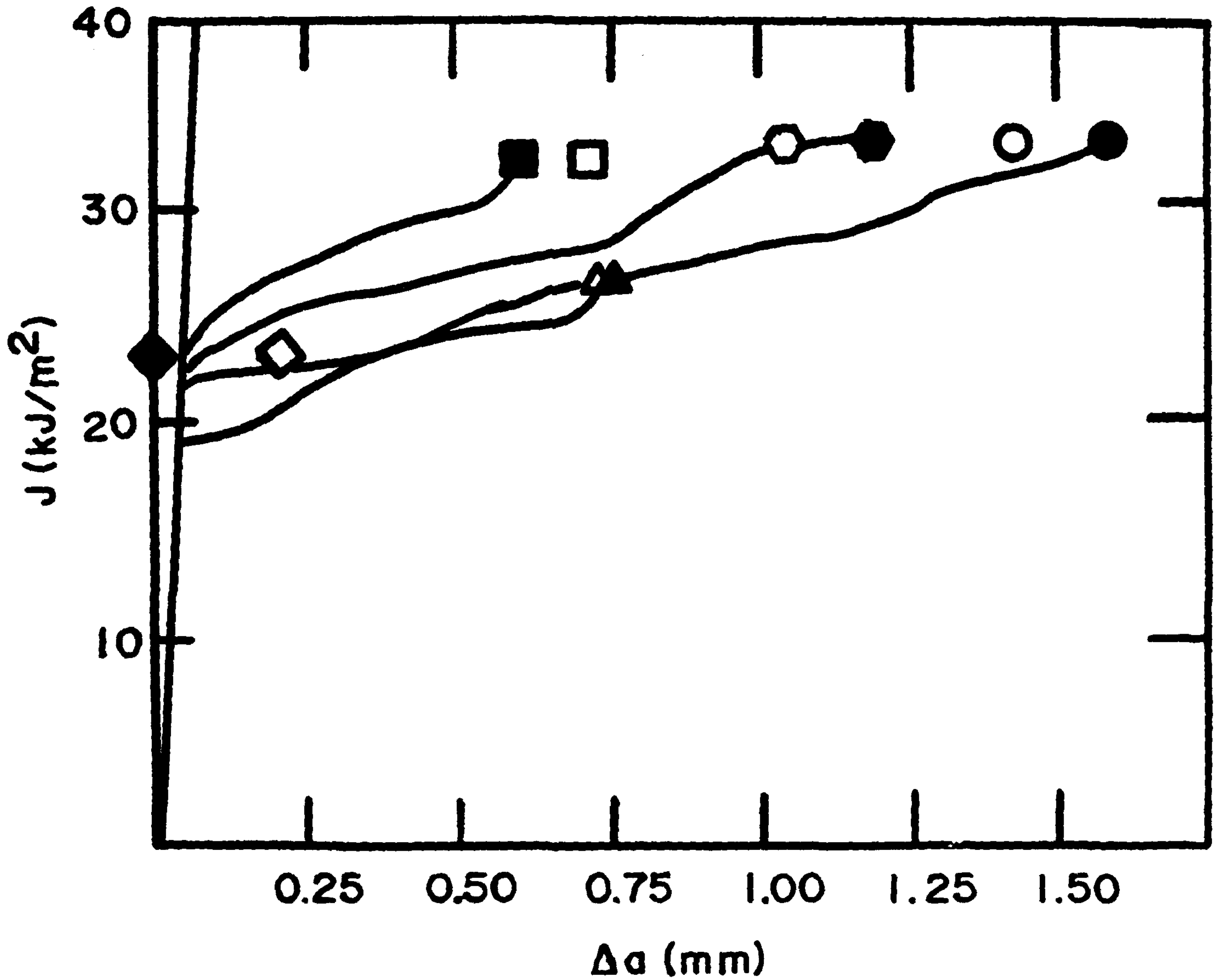

Figure 6. The multi-specimen data for 7075-T7351 aluminum. The open symbols are the fracture surface measurements of crack extension. The solid symbols are the estimated amounts of total crack extension from "load-drop," and the curved lines are the "load-drop" estimate of the entire J-R curve for each sample.

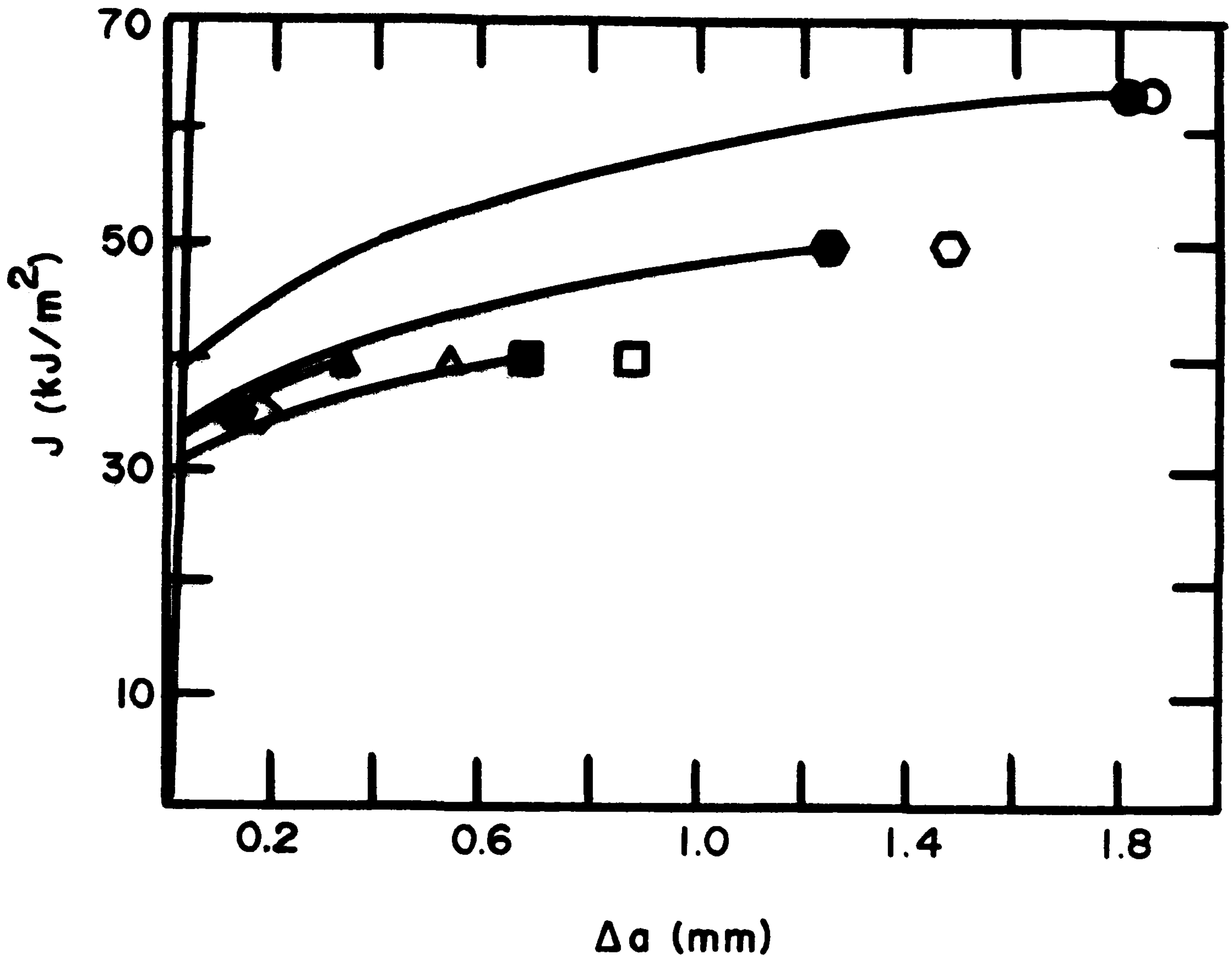

Figure 7. The results from testing of 6Al-4V-titanium. Open symbols represent the fracture surface measurements of crack extension. The solid symbols are the "load-drop" estimates of total crack growth and the curves are the "load-drop" estimates of the J-R behavior of each sample.

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